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ACTIVE MATERIAL CYLINDER FIBERS

Syracuse University

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13. ABSTRACT (Maximum 200 words)

The objective of this effort was to fabricate fiber optic cable with optically active material at the core cladding interface. It was discovered that there are a large number of parameters that can be varied to fabricate exactly the device required for a particular application. Much of the effort on this task was used to acquire the proper glasses and alloys required to actually draw usable fibers. Although we were unable to fabricate a fiber amplifier, we did learn enough about semiconductor materials in glass to be able to fabricate these devices in the near future. We were able to fabricate a polarization preserving fiber by depositing an AlCu alloy on the preform. Fiber drawn from this preform had the desired polarization preserving capabilities, making it a very useful device in any application requiring polarization maintaining characteristics.

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ABSTRACT.

The work during this year was concentrated in two areas. We learned a great deal about the fabrication of fibers with an optically active material at the core cladding interface. We have also fabricated and measured the polarization dependence of the transmission spectrum of Metal Strip Polarizing Fibers. The measurements were performed at the Photonics Center of Rome Laboratories. These devices were fabricated by Syracuse University. We have shown that the metals survive the fabrication process. We where able to measure the plasma resonance absorption of the metal strips. Since the vacuum system with the computer controlled effusing sources took an unexpectedly long time to become operational little progress was made on **S**emiconductor **C**ylinder **F**iber **L**ight **A**mplifier.

As we have discovered this can be a very rich technology, that is there are an exceedingly large number of parameters that can be varied to fabricate exactly the device required for a particular application. Glasses of various working temperatures, expansion coefficients, and indices of refraction can be fabricated. Indeed, glass is a 5 000 year old technology and a great deal is known about glass. Metal alloys with various optical properties, melting points and pliability can be fabricated. Semiconductors with various optical properties can be made. Indeed, potentially a greater variety of devices can be fabricated with this technology than with the semiconductor technology that revolutionized society in the last half of the 20th century.

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1. INTRODUCTION

We are using this report, the report for the Summer 1995 AFOSR Summer Faculty Research Program entitled “Metal Strip Polarizing Fibers”, and the report for the 1993/1994, Expert in Science and Engineering contract to document the progress on a new technology. This technology consists of placing optically active materials between the core and cladding of an optical fiber. A common property of these devices is that they are only a few mm long. We hope that other better equipped research groups would take up this work.

This work started with the successful fabrication and test of fibers with a core surrounded by a thin semiconductor cylinder about two years ago. The results were very reproducible. It should be possible to use multiple layer semiconductor cylinders to fabricate **S**emiconductor **C**ylinder **F**iber **L**ight **A**mplifiers (SCFLAs) and Fiber Lasers. The immediate application is for optical communication. Perhaps, eventually, these SCFLAs can be assembled into Fiber Light Amplifier Plates to be used in eye glasses, etc. Fibers with single semiconductor layer cylinders can be used as non linear elements in optical switches. Fibers with metal strips adjacent to the core can be used as polarizers. Fibers with magnetic material cylinders polarized along the fiber axis in conjunction with metal strip fiber polarizers can be used as isolators, etc. We report both on new devices and new knowledge gained about fabricating techniques.

This is a very rich technology, that is there are an exceedingly large number of parameters that can be varied to fabricate exactly the device required for a particular application. Glasses of various working temperatures, expansion coefficients, and indices of refraction can be fabricated. Indeed, glass is a 5 000 year old technology and a great deal is known about glass. Metal alloys with various optical properties, melting points and pliability can be fabricated. Semiconductors with various optical properties can be made. Indeed, potentially a greater variety of devices can be fabricated with this technology than with the semiconductor technology that revolutionized society in the last half of the 20th century.

These fibers are made by depositing optically active materials on a thin glass rod. The glass rod, eventually, forms the core of the fiber. For materials that form cylinders surrounding the fiber core the glass rod rotates during deposition. The glass rod is inserted into a glass tube that is closed at one end. The tube is evacuated, heated and collapsed onto the coated glass rod. More tubes may be collapsed unto the first tube in order to obtain the appropriate ratio of core diameter to the outside diameter of the cladding. This forms the preform. The components of the cross section of the preform have the same proportions as the components of the cross section of the fiber. A fiber is drawn from this preform. As we have found the temperature and speed at which the fiber is drawn is almost as critical as the materials used in the fiber.

This report deals with **M**etal **S**trip **P**olarizing **F**ibers (MSPFs) and new knowledge gained in fabricating optical active material cylinder fibers.

Some of the progress by us has been frustratingly slow mainly do to equipment problems. For example, we needed a vacuum system with individually computer controlled effusion sources to deposit compound semiconductors such as $Pb_xCd_{1-x}S$. We build the pumping station of the vacuum system out of salvaged and junk parts. The structure that holds the four effusion sources with shutters, three glass rods that can be rotated during deposition, and radiation substrate heaters was built in the machine shop at Rome Laboratories. To get the vacuum pumping station to work took an incredibly one year! We use a 30 year old vacuum system for metal deposition. This vacuum system periodically breaks down and has to be fixed.

The interaction of light with the various materials at the core cladding interface is only strong in weekly guiding single mode fibers. Indeed, we present a calculation demonstrating this fact. However, in order to fabricate weekly guiding single mode fibers it is necessary to have thin glass rods and tubes with a specific working temperatures and indices of refraction. The proper glass was much more difficult to obtain than we thought.

As we progress with this technology a tall fiber drawing tower where the drawing speed and temperature can be controlled becomes essential. We do have a commercial drawing tower and an experimental drawing tower/glass lathe. However, non of these towers are installed as of this date. Therefore, we hope that other better equipped research groups would take up this work.

2. ELECTRIC FIELDS AND MAGNETIC FLUX DENSITIES IN AN OPTICAL WAVEGUIDE

Light propagating through a symmetric slab waveguide with an active optical material at the slab waveguide cladding interfaces is similar to the propagation of light through an optical fiber with is an active optical material at the core cladding interface. However, the analysis of a slab wave guide with an optical active material layer at the core cladding interface is substantial simpler. Therefore, we here analyze the properties of the propagation of the TE modes through a symmetric slab waveguide with thin active optical material films between the waveguide slab and the claddings, see Fig. 1.

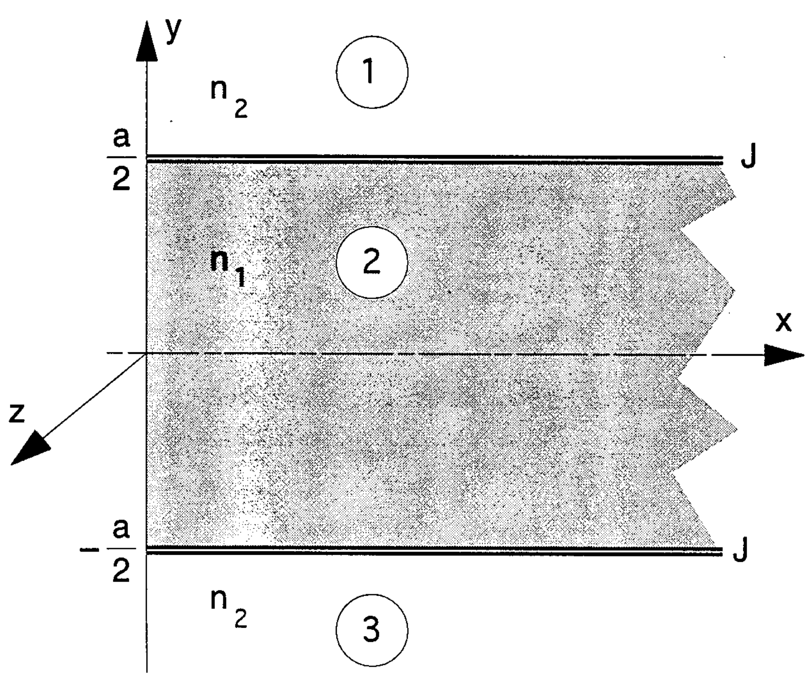

Fig. 1. Schematic representation of a metal clad symmetric slab waveguide.

In order for the slab to guide light the index of refraction n_1 of the slab has to be larger than the index of refraction n_2 of the surrounding material, the cladding. We assume that the optically active material sheets are sufficiently thin so that they can be represented by a current sheet with surface current density **J**, see fig. 2. We assume that the optically active film at the core cladding interface has an effective surface conductivity at light wavelength of σ Siemens per square.

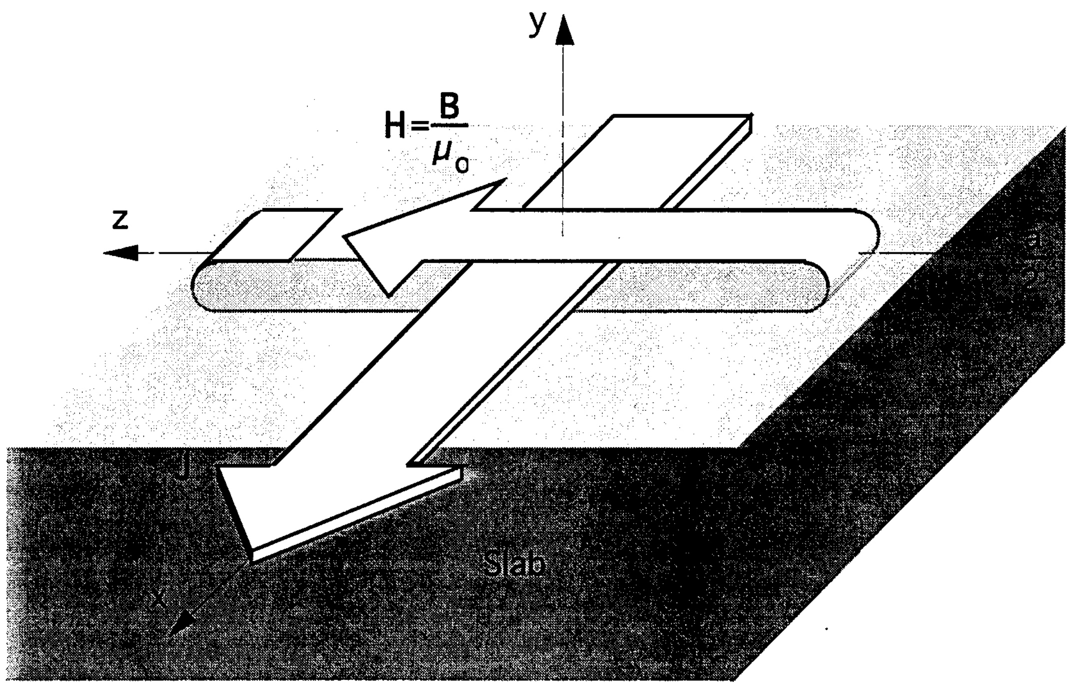

Fig. 2. Current sheet and the magnetic field at the slab waveguide boundary.

We calculated the mode structure and the complex propagation constant for every mode in this structure. The attenuation of the light wave in the slab waveguide due to the thin optically active layers depends on the imaginary part of the propagation constant.

$$\text{Attenuation} = e^{-\alpha L}$$

where α is the imaginary part of the propagation constant and L is the length of the waveguide. We here only present the numeric results of this calculation.

Numeric calculations show the importance of the weveguide structure allowing only a single mode to propagate for strong interaction with optically active layers at the weveguide cladding boundary. We first calculate and tabulate the attenuation of individual modes of a multi mode and a single mode slab waveguide. However, the individual modes, except in the single mode slab waveguide, can not be observed. Therefore, we calculate the relative amplitude of each mode in a multi mode slab waveguide by expanding a uniform illumination in the modes of the waveguide, calculating the attenuation of each mode, and recalculating the output illumination by summing the attenuated modes, see Fig's 3, 4, and 5. Only the numeric results of these calculations are shown here.

The effective surface conductivity σ at light wavelength can be calculated from measuring the ratio of the reflected light power to the incident light power on a sheet of glass with a thin film having the same surface conductivity at light frequencies as the material at the core cladding boundary.

For a slab waveguide of thickness a = 110 μm, a wavelength of λ = 1.3 μm, an index of refraction n_1 of 1.487, an index of refraction n_2 of 1.484 resulting in a $V = \frac{2\pi a}{\lambda}\sqrt{n_1^2 - n_2^2}$ of 50.19294, a power reflection ratio of 10^{-4} as discussed above, and a waveguide length L of 6 mm we obtain the following attenuation of the symmetric and antisymmetric modes:

Mode	No.	Attenuation	Wavevector times slab thickness in units of π
Sym.	1	0.8923529	0.974592
Ant.	1	0.9762860	2.909298
Sym.	2	0.6148230	3.131474
Ant.	2	0.9217961	3.850435
Sym.	3	0.5433555	4.809050

Ant.	3	0.5566764	6.262949
Sym.	4	0.5047817	7.317425
Ant.	4	0.7201847	7.684894
Sym.	5	0.4952287	8.643508
Ant.	5	0.5383942	10.464880
Ant.	6	0.4697842	11.503380
Sym.	6	0.4826565	11.519350
Sym.	7	0.4793890	12.446010
Ant.	7	0.2614937	14.762660
Ant.	8	0.2287640	15.210020

For a single mode slab waveguide with thickness of a = 6 μm, a wavelength λ of 1.3 μm, an index of refraction n_1 of 1.487, an index of refraction n_2 of 1.484 resulting in a V of 2.737797, a power reflection ratio of 10^{-4}, and a waveguide length L of 6 mm we obtain the following attenuation of the single symmetric mode:

Mode	No.	Attenuation	Wavevector times slab thickness in units of π
Sym.	1	5.906064×10^{-5}	0.5586109

Note that the attenuation of even the highest mode of a multi mode slab waveguide is only 0.2287640, while the attenuation is equal to 5.906064 x 10^{-5} in a single mode slab waveguide. Indeed, the interaction of the light in the core of the guide with the material at the core cladding boundary is much stronger in a single mode guide.

We assume that the slab waveguide only, the region between y equal to $-\frac{a}{2}$ and $\frac{a}{2}$ in Fig. 1, is uniformly illuminated. We expand the light electric field in a series of the symmetric modes of the waveguide. As each mode travels the length of the waveguide it is attenuated as shown in the tables above. We recalculate the electric field profile from the attenuated electric field modes at the output of the slab waveguide. The output pat

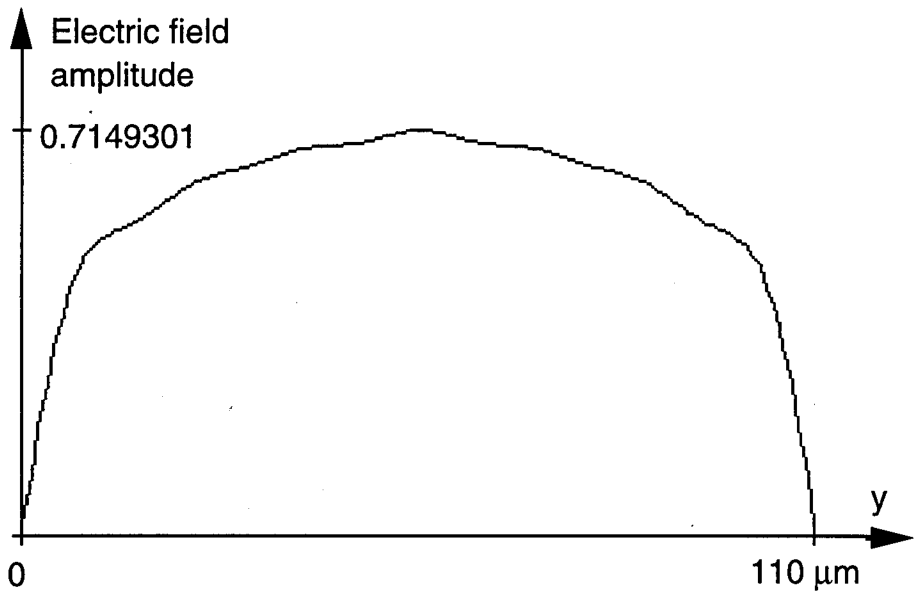

Fig. 3. Amplitude of electric field at output of 6 mm long multi mode slab waveguide. A power reflection ratio of 10^{-4} was used.

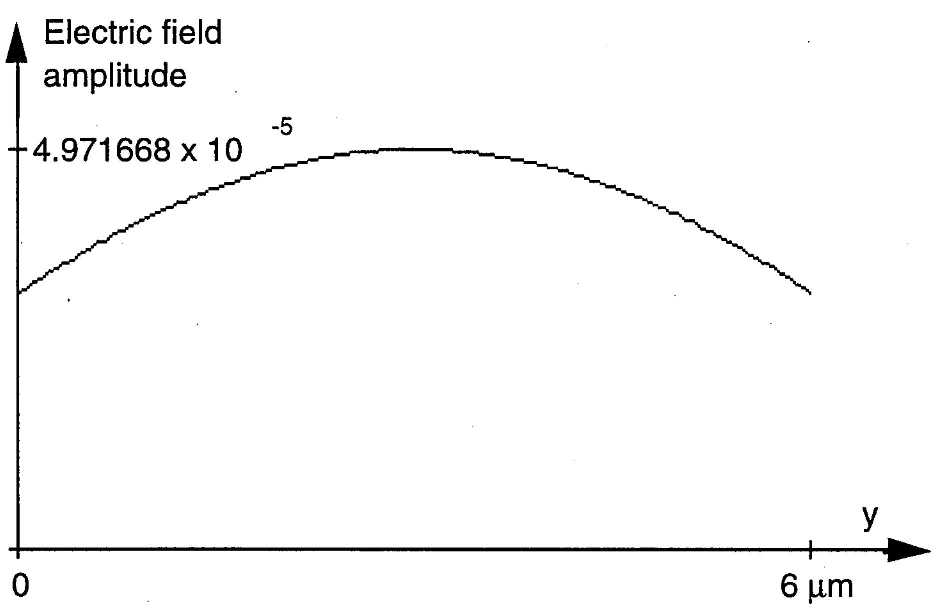

Fig. 4. Amplitude of electric field at output of 6 mm long single mode slab waveguide. A power reflection ratio of 10^{-4} was used.

tern of the electric field from a multi mode slab waveguide is shown in Fig. 3 and the output pattern of the electric field from a single mode slab waveguide is shown in Fig. 4.

We, again, observe that the interaction of the light in the core of the guide with the material at the core cladding boundary is much stronger in a single mode guide.

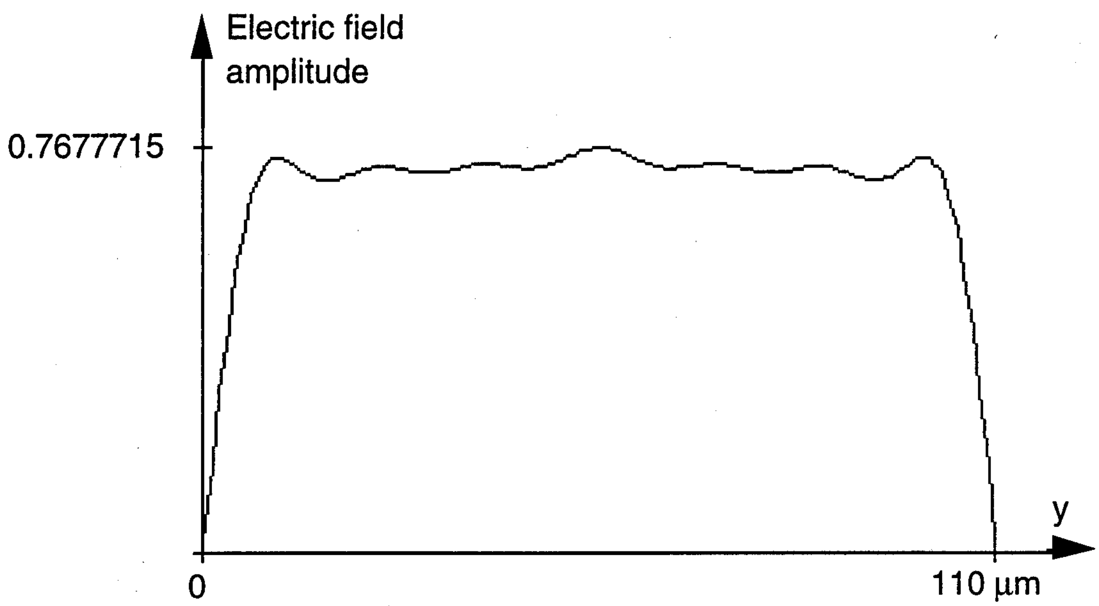

Fig. 5. Amplitude of electric field at output of 6 mm long single mode slab waveguide with no attenuation.

Note that since only a limited number of modes can propagate through the waveguide even the unattenuated electric field at the output is less than the unity input electric field in the multi mode slab waveguide, see Fig. 5. Thus the effect of the attenuation is only 0.9311756 or -0.619368 dB. This is, of course, also true for the single mode slab wave guide. Indeed, the output amplitude of a single mode slab waveguide with no attenuation has an output maximum of 0.817904.

3. METAL STRIP POLARIZING FIBERS

3a General Discussion

There are two purposes for investigating **M**etal **S**trip **P**olarizing **F**ibers (MSPFs). One is that these devices can be used as polarizing fibers. The other is that these devices allow us to study techniques for smoothly deforming, without tearing, the optically active material surrounding the core in the preform deforms in the fiber drawing process.

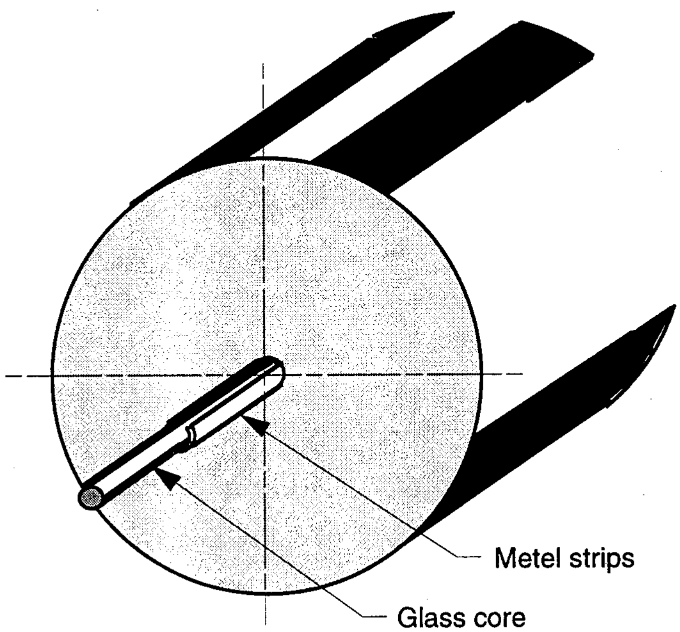

Fig. 6. Typical MSPF construction. The device consists of a glass core with two thin metal strips at the core cladding interface.

We have tested the transmission spectra and polarizing properties of MSPFs that were fabricated at Syracuse University. These devices are typically only a few mm long. The MSPFs consist of a glass core flanked on two sides by thin by a thin metal strips. That is the metal strips are located at the core cladding interface, see Fig. 6. Light polarized parallel to the metal strips is absorbed while light polarized perpendicular to the strips is not absorbed. We have used a variety of materials to fabricate these strips. We have used silver, copper and CdTe. A number of each type of fiber were fabricated by Syracuse University and tested at the Photonics Center of Rome Laboratories. Spectral measurements at the Photonics Center of Rome Laboratories showed that these materials survived the fiber fabricating process. The fibers had reproducible characteristics.

Several type of fiber polarizers have been constructed by other researcher[1,2]. A particular successful type was constructed by grinding away some of the cladding of in glass are a predecessor of this technology. SMs have a large number of surface states at their interfaces

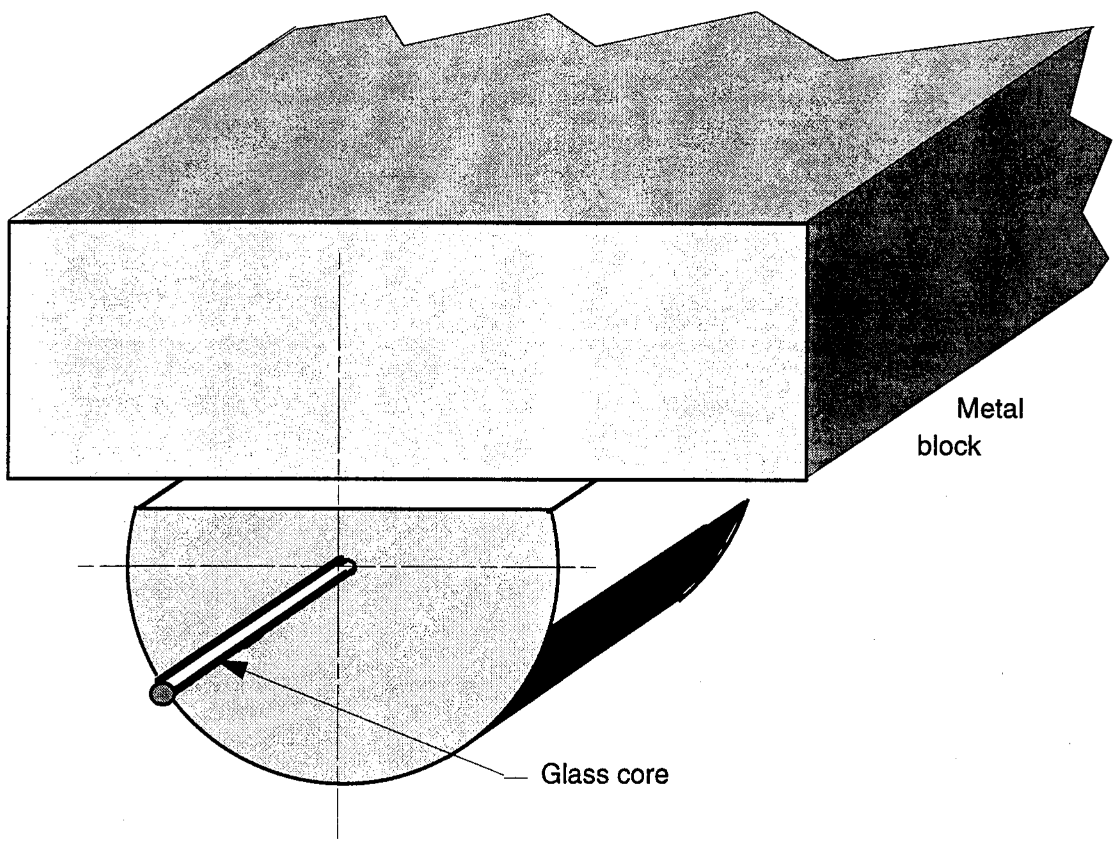

Fig. 7. D shaped polarizing fiber with metal block.

with the host glass. A metal block was placed in the space where the cladding was ground away, see Fig. 7. Extinction ratios of 70 dB have been reported for these devices.

Based on our successful experience of fabricating Semiconductor Cylinder Fibers (SCFs) which we have reported last summer we attempted to use the same techniques for fabricating MSPFs.

The 3M[3,4] company sells commercial polarizing fibers. However each of these is about 40 m long while the MSPF are only e few mm long.

3b MSPF Fabrication

The MSPFs were fabricated by, first, vacuum depositing metal film strips on two sides of a Pyrex glass rod that will form the core of the fiber in a diffusion pumped vacuum system. The glass rod is clamped in a mask as shown in Fig. 8 for this deposition process. A Pyrex glass was selected that has a softening temperature of 720 ^{o}C. This is lower than the melting points of the metals used.

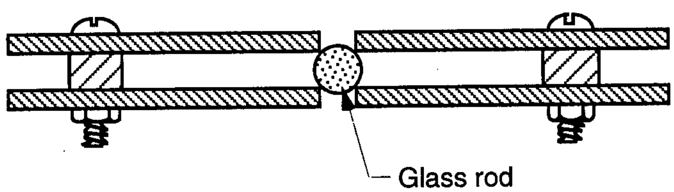

Fig. 8. Mask for vacuum depositing metal strips on core glass rod.

As discussed previously, the metal coated glass rod was inserted into a Pyrex glass tube that has been closed at one end. This structure is evacuated and collapsed. N_2 is used as the residual gas in the evacuation process. Finally, a fiber is pulled from the resulting preform.

3c Experimental Results

In order for this device to be practical it is necessary that only a single mode propagate in the fiber. This requires that the core have a sufficiently small diameter and that the core have a slightly higher index of refraction than the cladding. Unfortunately, we were not able at that time, to secure glass rods that have a sufficiently small diameter to yield sufficiently small fiber cores, and worth, the core and cladding glasses had the same index of refraction. We have since obtained glass with the desired properties. However, we here report on devices fabricated with the "old" glass. Recall, the Semiconductor Cylinder Fibers (SCF) that we tested last year had a similar problem. However, since the semiconductors completely enclosed the core it facilitated some guiding. This is not the case with the metal strips.

Several metal strip fibers were fabricated and tested. The metal films deposited on the glass rods where approximately 3000 Å thick. Since all components shrink proportionally in the fiber fabricating process by a factor of about 94 the metal films should have a thickness of about 32 Å. Not even a SEM could resolve these films. Therefore, we are having these films analyzed by a Scanning Force Microscope at Rome Laboratories. To date we are still waiting for these tests to be performed.

We here present the test results of Ag strip fibers. These fibers had approximately 35 μm diameter Pyrex glass cores and 80 μm diameter Pyrex glass claddings. Fibers of various length ranging from 120 mm to 12 mm length were tested. The 12 mm long devices worked best. The results presented here were for the 12 mm long fibers. As stated above material availability restricted us to use glass with the same index of refraction for both the core and cladding.

The following test arrangement was used: Light from a white light source was focused by a microscope objective into the fiber. Another microscope objective was used to retrieve the light from the fiber. An iris was used to block the light from the cladding. These fibers had exceedingly poor guiding. The light passed, next, through a Glen Thompson Polarizing Prism. Finally the light was focused into a ANDO type AQ 1425 optical spectrum analyzer connected to a computer. “Lab. Window” software was used to control the spectrum analyzer and record the data.

The data taking procedure was as follows: It is important to note that the spectrum analyzed is somewhat polarization dependent. A piece of MSP fiber was positioned in the fiber holder. Transmission date using the spectrum analyzer was recorded for consecutive angular positions of the Glen Thompson Polarizer. The data was taken in 10^{o} steps. The Glen

Thompson Polarizer was rotated a total of 180°. This experiment for exactly the same Glen Thompson Polarizer positions was repeated for a piece of standard multimode fiber which was used as a reference. The reason for this procedure is that the fiber could never be repositioned with the same angular position in the fiber holder. Of course, it is not possible to rotate the fiber and maintain optical alignment. The data from the multi mode fibers was used to normalize the date from the MSPFs. fibers. This limited the effect of the polarization dependence of the optical spectrum analyzer. The polarization dependence of transmission spectra of Ag strip as well as of CdTe strip fiber sections were obtained.

The normalized transmission spectrum of an Ag MSP fiber at Glen Thompson Polarizer positions of 78° and 168°, corresponding to minima

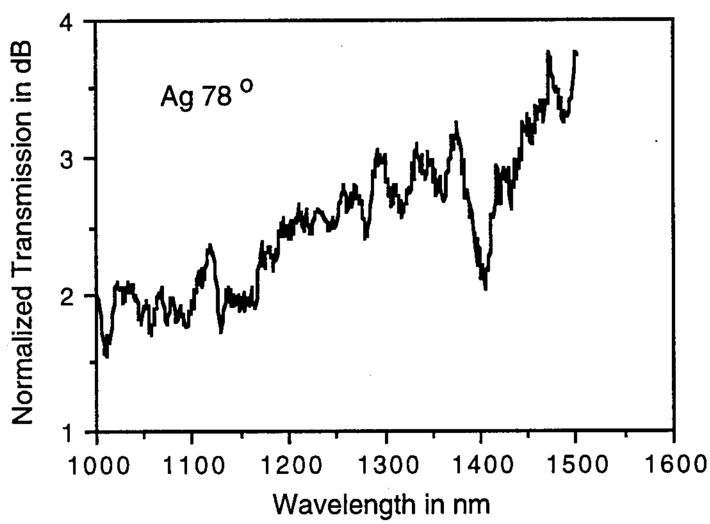

Fig. 9 Normalized transmission spectrum of MSP fiber for Glen Thompson polarizer position of 78°. This corresponds to the maximum transmission through the fiber. The "bulge" at about 1200 nm is the most significant part of the data. Note the OH absorption at about 1400 nm which is larger in the Pyrex fiber than in the commercial fiber.

and maxima of the transmission through the MSP fiber are shown in Fig's. 9 and 10. Of course, we have plotted data of these fibers in 10° polarization steps. dependence of the spectrum analyzer we analyzed the ratio of other normalized transmission spectra. For example, the logarithm of the ratio of the normalized transmission spectrum of date with the Glen Thompson Polarizer positioned at 118^{o} and 208^{o} as shown in Fig. 12. No resonance peak appears in this data. Of course, data with the Glen Thompson Polarizer adjusted to angles close to 168^{o} and 78^{o} exhibit smaller resonance peaks.

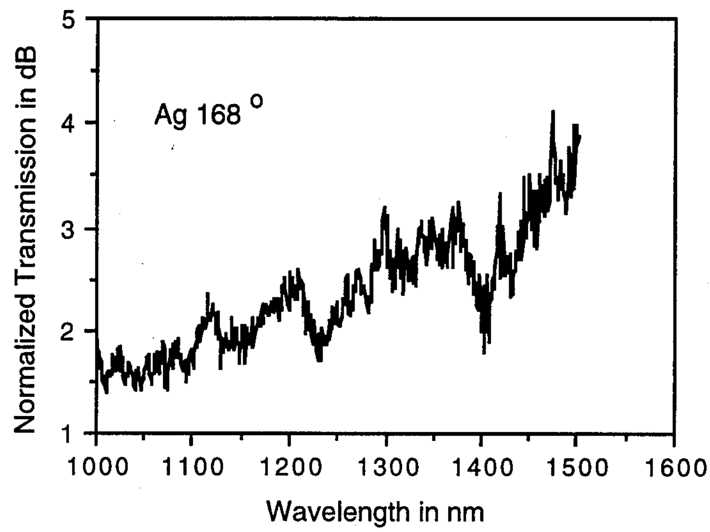

Fig. 10. Normalized transmission spectrum of MSP fiber for Glen Thompson polarizer position of 168^{o}. This corresponds to the minimum transmission through the fiber. Again, note the missing of the "bulge" at about 1200 nm. Note the OH absorption at about 1400 nm which is larger in the Pyrex fiber than in the commercial fiber.

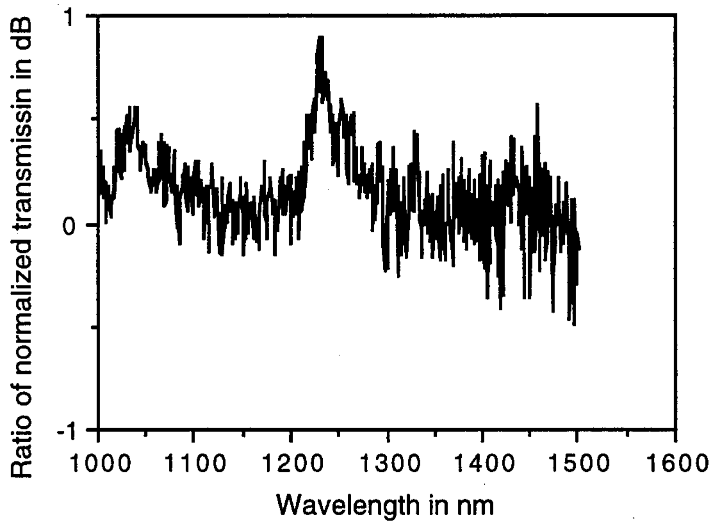

Fig. 11. Ratio of normalized transmission spectrum of MSP fiber for Glen Thompson polarizer positions of 168^{o} and 78^{o}. Note the plasma resonance peak at 1230 nm.

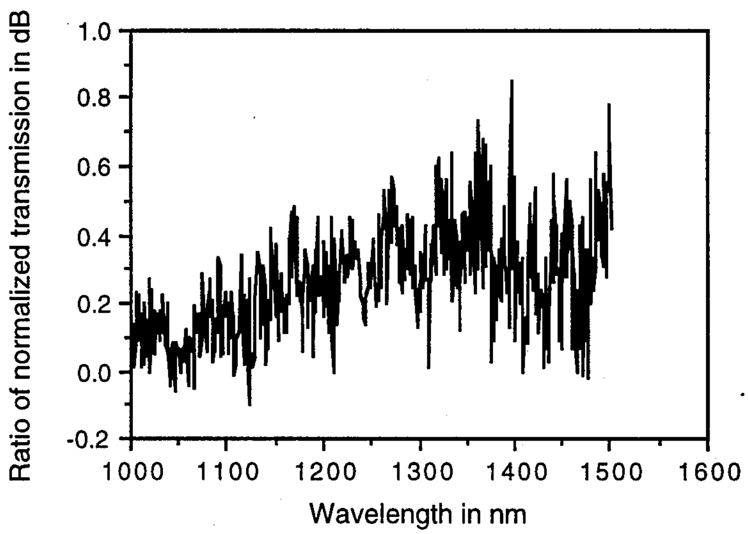

Fig. 12. Ratio of normalized transmission spectrum of MSP fiber for Glen Thompson polarizer positions of 208^{o} and 118^{o}. Note the absence of the plasma resonance peak at 1230 nm.

Metals exhibit plasma resonances at optical frequencies. We believe that the peak observed in Fig. 12 is a plasma resonance of the Ag film.

Of course, the present fibers with their large non guiding cores are not practically useful. Nevertheless, we were able to obtain some interesting data for the Ag strip fibers.

Syracuse University has glass on order that will allow the fabrication of single mode MSP fibers. To make these fiber polarizers commercially viable it is necessary to find metals that have plasma resonances near wavelength of 1.3 nm and 1.55 nm.

4. ACTIVE OPTICAL MATERIAL CYLINDER FIBER PULLING TECHNIQUE

It is necessary to for the metal that forms the active material strips in the fiber to have a melting point higher than the working temperature of the glass otherwise the metal will melt during the process when the tubes are collapsed onto the rod with the metal strips. On the other hand, the metal must be soft enough at the temperature of the fiber pulling process so that it will deform smoothly from its preform dimensions to the dimensions it has in the fiber without tearing. For MSPFs one can tailor the metal alloy to have the desired properties while in the **S**emiconductor **C**ylinder **F**ibers (SCFs) the glass has to be tailored to have the appropriate properties consistent with the thermal properties of the semiconductor materials. The deformation of the material surrounding the core in the preform occurs due to the pressure exerted by the surrounding glass during the fiber pulling process.

We have fabricate glass rods with vacuum deposited Al films. Since Al has a melting point of 660.2 ^{o}C and the working temperature of the our glass is about 710 ^{o}C the aluminum films melted and partially oxidized as predicted during the collapsing process. We used type 7052 borosilicate glass for the tubes and type 7720 borosilicate glass for the rods. We have tried Cu film strips. However, since Cu has a melting point of 1083 ^{o}C it appeared to be to firm to deform smoothly during the fiber drawing process. In fact, it tore into large pieces during the fiber drawing process as shown in Fig. 13.

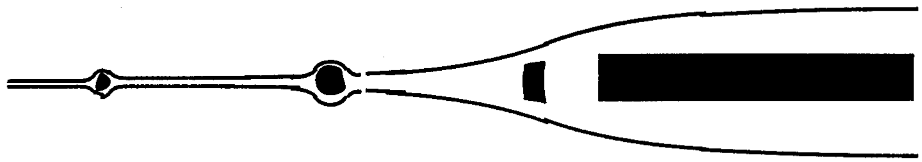

Fig. 13. The metal strip in the preform tears into large pieces during the fiber drawing process when the melting point of the metal is too large compared to the working temperature of the glass as was the case with Cu strips on type 7720 glass.

We subsequently used AlCu alloys with substantially better results. The proper alloy can be selected from an alloy table. The alloy table below is from "Hand Book of Chemistry and Physics" 47 edition 1966-1967 page D-97.

Percent Cu	0	10	20	30	40	50	60	70	80	90	100
Melting Point in ^{o}C	650	630	600	560	540	580	610	755	930	1055	1084

Since the metal films are formed by vacuum deposition a knowledge of the vapor pressure of the metals is useful. For example Al has a vapor pressure of 10^{-5} Torr at about 830 ^{o}C while Cu has a vapor pressure of 10^{-5} Torr at 1000 ^{o}C. This data is from vapor pressure graphs on page 298 of "Physics of Semiconductor Devices" by S. M. Sze 2'nd edition, John Wiley and Sons, ISBN 0 471 05661-8. In the metalization vacuum system used for fabricating the metal films only one thermal evaporation source at a time can be energized. Thus, in order to fabricate an AlCu alloy we placed about 35% Al powder and 65% Cu powder into single thermal evaporation source.

What ever the alloy was it survived the collapsing process and yielded a much smoother transition from preform to fiber with, at, first some tearing as shown in Fig. 14.

In SCF it will not be possible to mach the semiconductor to the properties of the glass as was done by alloying the metals. However, since a great variety of glasses can be fabricated it should be possible to mach the glass to the semiconductor properties. As we shall see below the optically active materials are deformed due to pressure from the surrounding glass rather than due to melting.

We have found, that the temperature and speed at which the fiber is drawn is almost as critical as the material used for the optically active film. Even the above discussed alloy when drawn at a high temperature where the glass becomes very soft tears almost as badly as shown in Fig. 13. However, when drawn at lower temperatures where it is necessary to apply a force to the glass in order to draw a fiber the metal deforms exceedingly smooth as shown in Fig. 15. That is, the metal is deformed due to the pressure of the surrounding glass rather than due melting.

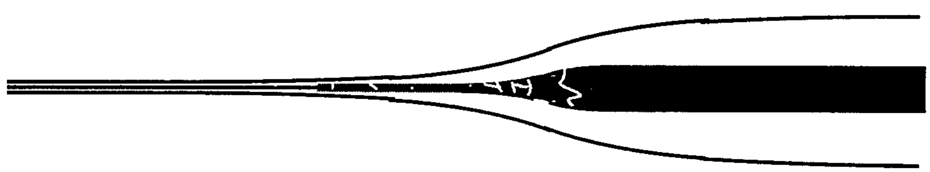

Fig. 14. When the melting point of the metal and the softening point of the class are matched closer the metal strip can still tear into smaller pieces during the fiber drawing process when the glass is too soft.

These fibers were fabricated by collapsing a single tube onto the rod. The effect of having a number of tubes collapsed onto the glass rod which is required to yield single mode fibers with appropriate outside diameter is still to be studied. We expect that since glass is a poor conductor of heat and since the outside of the glass of the preform is heated by contact with the flame of the burner the inside of the preform near the metal strips should have a lower temperature than the outside of the glass preform during fiber drawing. Thus the glass near the metal should be quite firm and able to deform the metal by pressure.

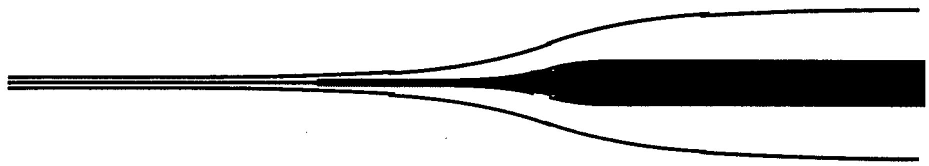

Fig. 15. When the melting point of the metal and the softening point of the class are matched closer and the fiber is drawn at a sufficiently low temperature where the glass is relatively firm compared to the metal the metal strip will deform smoothly during the fiber drawing process.

The optical properties of the alloy MSPF are still to be tested. Indeed, we have learned a great deal about the new technique of fabricating fiber with optically active cylinders. As the work progresses we learned that there are a very large variety of devices that can be fabricated by this technique.

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